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Characteristics of an Atmospheric Discharge Plasma as an RF Antenna.

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The plasma produced by a laser-guided, electric discharge in the atmosphere has been formed in the shape of a folded monopole antenna with a characteristic frequency of 112 MHz. This plasma antenna has been used to transmit and receive signals at 112 MHz. While the plasma conductivity remained above a certain value, the signal transmitted from, and received on, the plasma antenna was within -1 ±1 dB of that transmitted from and received on a "standard" copper folded monopole antenna of the same size. During this time the signal transmitted from, and received on, the plasma antenna also remained approximately constant in amplitude (fluctuations ~ ±1 dB). This useful

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20. ABSTRACT (Continued)

lifetime of the plasma antenna was varied from ~200 μs to $\gtrsim$ 2000 μs by changing the duration of the electric discharge sustaining the plasma columns.

In these experiments, the noise from the plasma antenna was not distinguishable from that developed using a copper antenna, but in both cases the noise was much larger than the true thermal noise background.

CONTENTS

CHARACTERISTICS OF AN ATMOSPHERIC DISCHARGE PLASMA AS AN RF ANTENNA

I. Introduction

Soon after the discovery of solid state lasers[1] it was observed that plasmas are created when sufficiently intense laser beams are focused in air at atmospheric pressure. The first studies of this phenomenon were reported in 1963[2] and 1964[3]. Two years later a patent was issued for the laser triggered spark-gap switch[4] and in 1968 a patent covering the use of laser-produced plasmas as antennas or antenna arrays was issued.[5]

Lasers themselves and the laser triggered spark gap switch are widely used but the use of laser-produced plasmas as antennas has probably never been demonstrated. Though its technical feasibility cannot be disputed, the consumption of large quantities of energy to produce and sustain an atmospheric plasma by the absorption of laser radiation has never been deemed worthwhile. On the other hand if only a small amount of laser energy were used to designate the shape (path) of the plasma antenna and energy to create and sustain the plasma were supplied directly in the form of an electric discharge a totally new balance of utility versus cost would be achieved. Such was the intent of the concepts patented by Vaill[6] and Tidman[7] in 1973, when they advocated the use of plasmas produced by laser-guided electric discharges in the atmosphere as the conducting elements of antennas or antenna arrays.

Theoretical[8] and experimental[9,10] support for the claims put forward by Vaill and Tidman has grown steadily over the years. Though initially the electric discharges were "straightened" rather than guided by the laser it was already known that laser-induced air-breakdown could be extended to at least 25 m.[11] More recently in a series of experiments at the Naval Research Laboratory it has been shown that electric discharges can be guided through the atmosphere along paths markedly different from the natural breakdown path by laser-induced, aerosol-initiated, air-breakdown. These experiments used either a CO_2 laser[12,13] or a Nd:glass laser,[14] and in the latter case showed that the laser energy can be reduced to ~ 15 J/m of discharge length. They also showed that for an electric discharge to follow the very low level of pre-ionization provided along the laser-designated path, the discharge voltage must exceed a threshold value of ~ 125 kV. However once this high voltage discharge has been guided along the laser-designated path, secondary discharges of much lower voltage (down to 100 V) readily follow the more highly ionized path that now exists. Using these techniques very long duration (≥ 1 ms) guided discharges[15] were created, and the transport of an intense charged particle beam along a reduced-density, current-carrying channel in the atmosphere was demonstrated.[16]

In this paper we report the successful completion of a proof-of-principle experiment in which the plasma produced by laser-guided, electric discharges in the atmosphere has been used as both a transmitting and a receiving antenna. Experiments were conducted using a radio frequency of 112 MHz which was well clear of the higher frequencies used in commercial FM broadcasting and was found to be not used in local ILS and VOR communications. (The specific frequency used was determined by searching for an unused frequency above 100 MHz.)

Manuscript submitted March 2, 1982.

II. The Experimental Arrangement

To effect the proof-of-principle experiment and to determine the characteristics of the plasma antenna, the experiment shown schematically in Fig. 1 was conceived. A_1 represents the plasma antenna being used as the transmitter. A folded monopole geometry was chosen for the antenna because both ends of the antenna are readily accessible providing compatibility with the techniques used to form the plasma. Also it has nondirectional properties and well known characteristics. A_2 represents a reference folded monopole receiving antenna made out of 3/4 inch o.d. copper pipe. As indicated schematically in Fig. 1 the plasma antenna consisted of two vertical plasma columns, P_1 and P_2, whose positions were designated by the beam from an Nd:glass laser, NL. To maintain a precise antenna geometry, the two plasma columns were made to intersect with a short copper rod that was suspended at the desired height above the ground plane, G. The electric discharge that created the plasma antenna was driven by the high voltage power supply, D, and terminated in the discharge ground, G_2. The RF signal from the transmitter T, was injected near the discharge ground, G_2, and terminated in the RF ground, G_1. Details of the electric discharges and the various connections are described in Sections III and IV, respectively.

The radio frequency for this proof-of-principle experiment was chosen using the following considerations. The wavelength had to be long enough to require a reasonable antenna length compared to the typical plasma column radius of ~ 1 cm, but short enough that the required antenna length ($\lambda/4$) did not exceed our present capability in the length of the laser-guided discharge ($\lesssim 2$ m). Thus a frequency close to, but larger than, 100 MHz was indicated and a search of this region of the RF spectrum using the receiver, showed a quiet zone at 112 MHz. The bandwidth of 1 MHz was chosen to permit signal modulation at frequencies up to ~ 1 MHz. This produced RF signals that were clearly recognizable even during the short life-time of the plasma antenna. The power transmitted in these experiments was ~ 0.2 watts.

Given the wavelength ($\lambda = 268$ cm) of the signal to be transmitted, the separation between the antennas, A_1 and A_2, needed to be several wavelengths to ensure the existence of far field coupling only, similarly the antennas had to be situated so that there were no obstructions (conducting walls, ceilings, etc.) within many wavelengths. Fortuitously the building in which the Nd:glass laser and high voltage equipment were housed is a single story building with a flat unobstructed roof which is almost 61 meters square. The experiment was, therefore, performed on the roof of the building. The laser beams and the high voltage power were "piped" up through a hole in the roof and a small wooden enclosure (a cube approximately 2.44 m on the side) was built over the hole. This enclosure and a general view of the roof are shown in Fig. 2.

The plasma antenna was always created inside the wooden enclosure (for reasons described in Section III); it was ~ 17 m from the West edge of the roof and ~ 27 m from the South edge of the roof. The second antenna, A_2 in Fig. 1, was placed ~ 17 m due South of the plasma antenna. Both antennas were 67 cm tall with their vertical elements separated by ~ 10 cm, and both antennas were made to stand on 1 m by 1 m sections of ground plane made from copper screen. To accommodate the high voltage connections on the roof, the ground plane, G in Fig. 1, for the plasma antenna was ~ 1.5 m above the plane of the roof, while the ground plane, G^1, for the second antenna, A_2 was placed directly on the roof. Since our primary experiment consisted of a direct comparison of the signal received at A_2 using the reference copper antenna for A_1 to that received at A_2 using the plasma antenna as A_1, this difference in ground plane heights did not affect the result.

In secondary experiments (i) the reference copper antenna was compared to a "100 Ω" antenna [an antenna made from eight 12 ohm Allen-Bradley resistors connected together in series with heavy gauge copper wire in the shape of a folded monopole antenna]; (ii) the plasma antenna was used as the receiver; and (iii) an "all plasma" antenna was made (and used) by removing the copper rod used in the primary experiment and tilting the laser beams (toward each other) so that the two plasma columns intersected each other. The purpose of the "100 Ω" antenna was to provide an antenna with resistance comparable to that anticipated for the plasma antenna.

III. Production of Laser-Guided, Electric Discharges

The technique of producing laser-guided, electric discharges in the atmosphere has been extensively studied at NRL[12-16] and lends itself to the creation of a plasma antenna in the folded monopole configuration. As indicated in Fig. 1, the beam from the Q-switched, Nd:glass laser (100 J in 40 ns) passed through a long focal length lens (L; f.l. ~5 m) and was immediately split into two equally intense, converging beams. These beams (see also Fig. 3) were directed upwards and came to focus inside the wooden enclosure on the roof. The vertical beams were parallel and ~10 cm apart. The intensity in the beam waists exceeded the threshold for aerosol-initiated air breakdown over a distance of ~1.5 m and by igniting a small amount of black powder (~1 g) inside the wooden enclosure, the aerosol content of the air was enhanced to $\sim 10^{-7}$ g/cm^3. Thus two strings of profuse breakdown beads ~1.5 m long were created along each laser beam (Fig. 4). The expanding air plasmas produced by these breakdowns coalesced after ~30 μs to define weakly ionized paths through the air. A short segment of copper wire bridged the upper ends of these paths to complete the folded monopole configuration. The wire was suspended on an insulated stalk from the roof of the wooden enclosure and enabled us to accurately define the length of the plasma antenna for this study. When the high voltage pulse (typically ~250 kV) was applied to one end of this configuration (Fig. 3) an electric discharge followed the defined path and two highly conducting plasma columns were created. An open shutter photograph of such a discharge is shown in Fig. 5.

The electric discharge was provided by a small Marx generator (HV1 in Fig. 3; $V \leqslant 360$ kV, stored energy ~1000 J) which was located inside the building directly below the hole in the roof. A high voltage coaxial line (C in Fig. 3) transmitted the pulse from the Marx generator through the hole in the roof into the wooden enclosure. As shown in Fig. 6, this line was oil insulated and of sufficient dimensions (3/4 inch o.d. inner conductor; 3 inches i.d. outer conductor) to prevent internal arcing. In addition the HV connections at both ends were made under oil. An RG-220 center conductor with its polyethylene jacket was used to connect the top of the line to the discharge and a copper braid connected the outer conductor of the coaxial line to the ground plane (see Section IV).

The electric discharge from the Marx generator lasted only ~7 μs (about 3 cycles) and most of the ohmic heating occurred during the first half cycle (Fig. 7). The energy deposited by the Marx discharge was ~3 J/cm along the length of the discharge and was significantly larger than that deposited by laser heating and any subsequent RF heating.

Previous studies[14] have shown that although the plasma column created by the Marx discharge starts as a narrow filament (radius ~1 mm), it grows rapidly reaching a radius of ~2 mm within ~1 μs. Subsequently the plasma cools by nearly adiabatic expansion reaching pressure equilibrium with the surrounding atmosphere in $\lesssim 30\mu$s. At ~100 μs after the initiation of the Marx discharge the plasma column has achieved approximate thermal equilibrium at $T_e \sim T_g \sim 5000$ K, $n_e \sim 10^{14}$ cm^{-3}, $\rho/\rho_0 \sim 1/20$, and radius ~1 cm. While the discharge current is flowing the resistance of the plasma column is ~4 Ω/m. At ~30 μs the resistance has increased to ~20 Ω/m, and at ~100 μs the resistance is ~100 Ω/m. Thereafter fluid turbulence[17] within the plasma columns begins to mix the hot discharge gas with cold outside air: the columns, therefore, grow in radius as they become colder and denser, and their resistance grows exponentially.

To extend the useful lifetime of the plasma antenna, a secondary, sustaining discharge was passed through the plasma columns created by the Marx discharge. A modest capacitor bank (HV2 in Fig. 3; 180 μF, 20 kV) physically located near the Marx generator, was connected to the bottom end of the HV coaxial line through an explosively driven, closing switch (S in Fig. 3). The switch remained open while the Marx generator discharged and was closed (on command) ~60 μs later to initiate current flow from the capacitor bank. The secondary discharge was highly over-damped. With the capacitor bank charged to ~10 kV, the peak current of the secondary discharge was ~1 kA which damped with an RC time of ~2 ms. The current followed the path established by the laser/Marx discharge and maintained the integrity of the plasma antenna (Fig. 8).

IV. The High Voltage and RF Connections

As indicated in Fig. 1 the connections to the plasma antenna were complicated by the desire to transmit (or receive) RF signals measured in volts (or millivolts) from an antenna connected to a high voltage power supply (10 to 250 kV, 1 to 10 kA). To achieve this the folded monopole geometry was used to its full advantage; one side of the antenna was connected to the high voltage power supply (D in Fig. 1) while at the same time appearing to be a ground (G_1) for the RF, and the other side of the antenna was made to behave as a ground (G_2) for the high voltage discharge while being a suitable injection point for the RF signal. The frequency range for the high voltage discharges was dc to $\sim$350 kHz while the frequency for the radio transmission was 112 MHz, therefore the required connections could be made using suitable tuned stubs. Details of these connections are shown in Fig. 9. On the left side of Fig. 9, the high voltage connection to the plasma antenna was made simply by bringing the lead from the top of the HV coaxial line, HV, parallel to the laser-designated path, L_1, up to the level of the ground plane, G. The lead was terminated in a corona ball with a small protrusion sticking out towards the laser-designated path. The end of the protrusion was $\sim$1 cm from the path. There was a hole in the ground plane ($\sim$12.5 cm diameter) to accommodate the high voltage lead. To make this side of the antenna behave as a ground at 112 MHz, the ground plane was extended down around the high voltage lead for a distance of 67 cm ($\lambda/4$), thus forming the tuned stub, S_1. The extension to the ground plane was made of 5 inch diameter brass tube and to discourage spark breakdown directly from the high voltage lead to the ground plane a section of insulating tube, I, (a lucite tube with 1/4 inch wall thickness) was clamped inside the brass tube so that its ends extended well beyond the ends of the brass tube as indicated. Furthermore corona rings (not indicated in Fig. 9) were put on the sharp corners at both ends of the brass tube.

On the right side of Fig. 9, the ground connection for the high voltage discharge was made via two coaxial conducting pipes, which were joined together by an annular conducting plate at their lower ends (S_2 in Fig. 9). As indicated the laser beam, L_2, passed vertically through the smaller of these two pipes (a 1.5 inch i.d. copper pipe) and the discharge terminated on the upper, open end of this pipe. The length of this coaxial connector was again 67 cm so that when the 112 MHz RF signal was applied between the inner and outer conductors at the ground plane it behaved as a 1/4-wave shunt (an open circuit). Both stubs were tuned to optimum length by comparing the phases of incident and reflected signals on a coaxial lead terminated with the stub.

To accommodate these stubs, the high voltage leads and the RF connections in the wooden enclosure on the roof (the hole in the roof was only 12 inches × 12 inches which just permitted the HV coaxial line and the two laser beams) the ground plane, G, was placed $\sim$1.5 m above the surface of the roof as noted in Section II. Then to prevent unwanted transmissions from the connections, the area under the ground plane was made into a copper-screened enclosure.

The only other pieces of apparatus placed in the wooden enclosure on the roof were a dual-directional coupler, an adjustable line, and a tuned stub (DC, AL, and TS in Fig. 10). The tuned stub (a length of RG8 cable)/adjustable line combination was used to match the $\sim$135 ohm folded monopole antenna to the 50 ohm cable. Then by observing the signals from the dual-directional coupler, variations in the characteristics of the plasma antenna could be determined. The dual-directional coupler and the tuned stub were placed in a separate copper-screened enclosure.

Since the second antenna, A_2, which is shown in Fig. 10 as the receiver, was never used in a comparative situation, it was not necessary to match that antenna to its 50 ohm cable. In all experiments, A_2 was a reference copper antenna.

V. Experimental Results

The transmitter/receiver system, shown schematically in Fig. 10, was first set up using two identical, copper antennas, the reference folded monopole antennas, and the various stubs were tuned. A modulator, M, was used to control the output from the RF oscillator, O, so that the signal was easily identified. For convenience in the different experiments the transmitted pulse width was varied from $\sim 2\ \mu s$ to $20\ \mu s$ and the pulse separation was varied from $\sim 10\ \mu s$ to $\sim 100\ \mu s$. The signals from the dual directional coupler were displayed directly on a fast oscilloscope. The signal from the receiver, RE, was taken from the IF stage and again displayed on a fast oscilloscope. The AGC in the receiver was disabled so that the signal taken from the receiver was directly proportional to that received at the antenna. The system was calibrated by connecting the receiver directly to the transmitter through a calibrated attenuator. The transmission frequency and bandwidth were chosen as described earlier (Section II) and the background noise on the receiving system was measured as equivalent to $\sim 10^{-10}$ watts/MHz at the antenna when no signals were being transmitted but the transmitter was "switched-on."

Measurements were made with no antenna at A_1, with the "100 Ω" antenna at A_1, and with the plasma antenna at A_1. Both the laser/Marx discharge and the long duration discharge were used as antennas. In Table 1 the results are given as a VSWR for the transmitting antenna and as the ratio of the signal received using the test antenna to that received using the reference antenna. With no transmitting antenna, i.e., with no conductor protruding above the ground plane (G in Fig. 9) at the stub, S_2, the signal at the receiver was not measureable above the background noise. With the 100 Ω antenna as the transmitter, the received signal was about 1 dB below that received using the reference copper antenna as the transmitter. This difference was in fact difficult to measure because the output from the RF amplifier (AM in Fig. 10) drifted by approximately ± 1 dB over the typical experimental run. Using the plasma antenna as the transmitter, the received signal varied with time as the antenna was first created then died away. For the laser/Marx discharge typical records for the three signals are shown in Fig. 11. As can be seen the dual directional coupler was relatively unaffected by electrical noise generated when the plasma antenna was created. Figure 12 shows typical signals obtained when the plasma produced by the long duration discharge was used as the transmitting antenna. When the secondary sustaining discharge was fired, a significant transient which lasted for several hundred microseconds and had a peak amplitude ~ 1.7 volts measured on the oscilloscope, was superimposed on the dual directional coupler signals (Fig. 12a). This transient did not appear on the receiver signal (Fig. 12b).

The useful lifetime of the antenna produced by the laser/Marx discharge alone can be defined as the time during which the signal transmitted from the antenna i.e., that measured at the receiving antenna, remained essentially constant. From figure 11b this is seen to be approximately $250\ \mu s$ and typically varied between 200 and $300\ \mu s$. For the same discharge the signal reflected from the antenna (Fig. 11a) can be seen to reach a minimum value at approximately $200\ \mu s$, showing that the plasma antenna was best matched to the cable at that time. During its useful lifetime, the signal received from the laser/Marx-produced plasma antenna was about 2 dB below that received from the reference copper antenna (Table 1).

The useful lifetime of the antenna produced by the long duration discharge varied in the range 1.5 to 2 ms. A typical received signal is shown in Fig. 12b. As can be seen, the signal received from this plasma antenna varied more than that received from the antenna produced by the laser/Marx discharge, showing a distinct maximum around $600\ \mu s$. However a clear, usable signal was still received at times >2 ms after the antenna was first created.

For the following tests the coax cable coming from the second antenna, A_2 in Fig. 10, was connected to the RF amplifier and the coax cable coming from the dual directional coupler was connected to the receiver. In this way the plasma antenna at A_1 was used as the receiving antenna, and was again compared directly with a reference copper antenna. The result obtained is shown in the bottom line of Table 1. The signal received on the plasma antenna was about the same as that received on the reference antenna. Yet with no receiving antenna, i.e., no plasma, only a very small signal was received; this result is shown in the next-to-last line in Table 1. Few measurements were made in this configuration and the difference observed between the plasma antenna and the reference antenna was

Table 1 — Measured Antenna Characteristics

Transmitting antenna**	Receiving antenna	Transmitting antenna VSWR	Received signal dB*
Copper	Copper	2.78	0
No antenna	Copper	7.69	−24***
100 Ω antenna	Copper	2.78	−1
Plasma	Copper	3.45−2.04	−2
Copper	No antenna	—	−15
Copper	Plasma	—	+1

*Measured relative to copper/copper antenna system.
**The power incident on each antenna ~0.25 watts at 112 MHz.
***System noise, no perceptible 112 MHz signal; $\approx 10^{-10}$ watts/MHz.

not significant compared to the variability of the amplifier output. A typical received signal using the plasma antenna produced by the laser/Marx discharge as the receiver is shown in Fig. 13. On this time scale the "discharge" noise can be seen to extend for the first ~30 μs with an apparent restrike at ~130 μs. This noise looks as though it may be produced in the spark gap switches used in the Marx generator but no effort was made to identify the source. At other times the quiescent background signal—between signal pulses—was measured as representing a background noise signal at the receiving (plasma) antenna of ~10^{-9} watts/MHz.

Finally to demonstrate that the plasma antenna could be created without using a copper conductor suspended above the ground plane, the suspended copper wire was removed and both laser beams were tilted so that they intersected near the top of the enclosure. There was no difficulty making the Marx discharge track up one laser path, jump the gap, and come down the other laser path. However because the two laser beams were so close together - less than the distance that the Marx discharge can jump without laser-guiding, the height of the antenna could not be controlled. In Fig. 14, the discharge is seen jumping from one laser path to the other at the top of the insulator tube. (This insulator is shown in Fig. 9.) By increasing the length of the insulator an antenna of the correct height was created and used as a receiving antenna. The signal shown in Fig. 13 was in fact recorded from the plasma antenna which is shown in Fig. 14.

VI. Conclusion

Electric discharges guided through the atmosphere along paths designated by the beam from a Nd:glass laser have been used to create a plasma in the shape of a folded monopole antenna. This antenna which was tuned to a frequency of 112 MHz was used both as a transmitting antenna and as a receiving antenna in relatively short base-line experiments. The efficiency of the plasma antenna when transmitting or receiving was found to be very nearly as good (−1 ± 1 dB) as that of the reference, copper folded monopole antenna of the same dimensions. The useful lifetime of the plasma antenna was extended to ~2 ms by applying a long duration, "sustainer" discharge to the plasma column formed by the initial high voltage discharge.

Prior to performing these experiments, the very existence of gas discharge noise sources[18] led us to worry that the plasma antenna would be a very "noisy" antenna not suitable for normal communications. However closer examination[19] of the emission of such radiation shows that this is "thermal noise" and is limited to the "black body" emission of ~$kT\Delta f$, where k is Boltzmann's constant, T is the electron temperature, and Δf is the bandwidth. Even for an electron temperature of ~5000 K, thermal noise is only ~10^{-13} watts/MHz. Coherent radiation could produce stronger emissions at specific frequencies but for our weakly ionized plasmas at atmospheric pressure, the plasma characteristics are dominated by electron-neutral collisions which occur at a frequency of $\sim 10^{11}$ Hz. Thus we conclude that the plasma antenna should not be a significant noise source at 112 MHz and in fact the noise measured on the plasma antenna must have been generated in the modulated transmitter. Certainly when the transmitter was "switched-off", the true background noise measured using the copper reference antenna was only $\sim 7\, kT\Delta f$, while the background noise received on the reference antenna with the transmitter "switched-on" but nominally not transmitting (controlled by the modulator) was very nearly the same as for the plasma antenna, i.e., $\sim 10^{-10}$ as compared with $\sim 10^{-9}$ watts/MHz.

With the presently available laser and high voltage equipment the frequency range over which the plasma antenna can be tuned is limited by the length of the laser-guided discharge to $\geqslant$ 75 MHz. But results obtained so far[11,14,20] suggest that the lower frequency limit could be pushed to $\sim$10 MHz or even less. Furthermore there appears to be no obvious reason why the "sustainer" discharge should not be repeated at a frequency of up to $\sim$100 Hz to produce a plasma antenna that would be available on a pulsed/cw basis. Such an antenna would have many applications.

VII. Acknowledgment

The idea of the plasma antenna is not new and the results presented here can mostly be attributed to the efforts put into a series of experiments which have been performed at the Naval Research Laboratory over the last ten years or more. However one of us (J.M.P.) was introduced to the idea of the plasma antenna quite recently by his colleagues Drs. H. Olds and J. Dickey from the David Taylor Naval Ship Research and Development Center, Annapolis.

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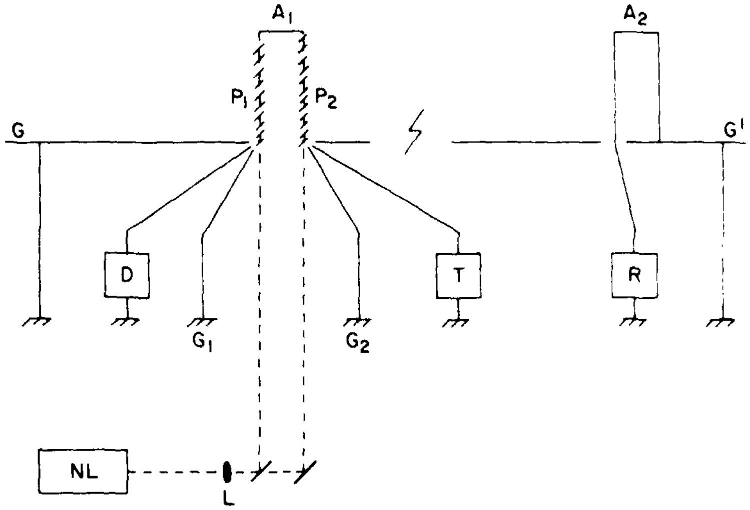


Fig. 1 — A schematic diagram of the RF propagation experiment. A_1 represents the plasma antenna rising above the local ground plane, G; A_2 represents a second antenna rising above its local ground plane, G^1. NL represents the Nd:glass laser whose beams --- define the plasma antenna. L represents the long focal length lens. D represents a high voltage system that drives the electric discharge and goes to ground at G_2. T represents the RF transmitter and G_1 the RF ground. R represents the receiver.

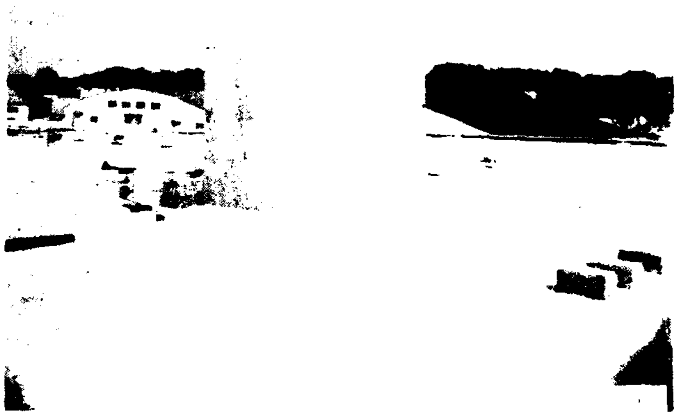


Fig. 2 — A photograph of the wooden enclosure in which the plasma antenna was created, and the roof-space where the RF experiment was performed.

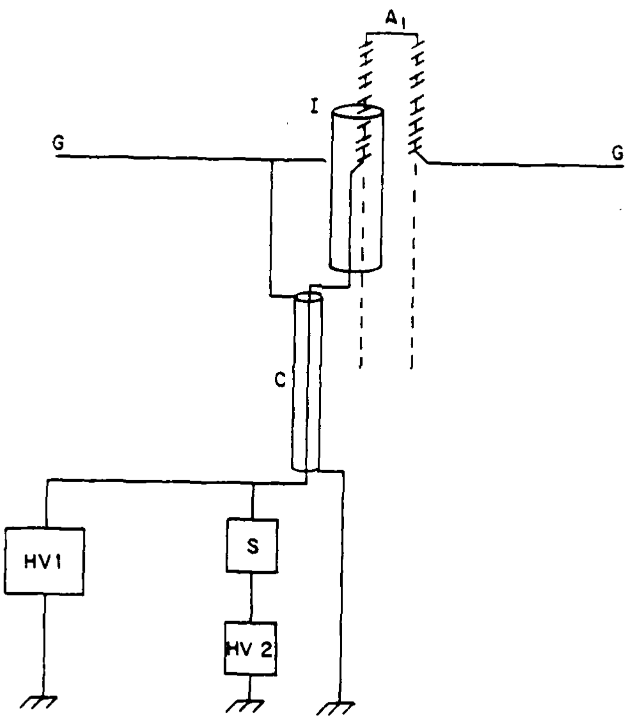


Fig. 3 — A schematic diagram of the high voltage system used to create the plasma antenna. HV1 represents the Marx generator ($\leqslant$360 kV); HV2 represents the capacitor bank ($\leqslant$20 kV). S represents the detonator activated, solid dielectric closing switch, and C represents the high voltage coaxial line. G is the local ground plane for the plasma antenna A_1 and I is a plastic tube used as an insulator.

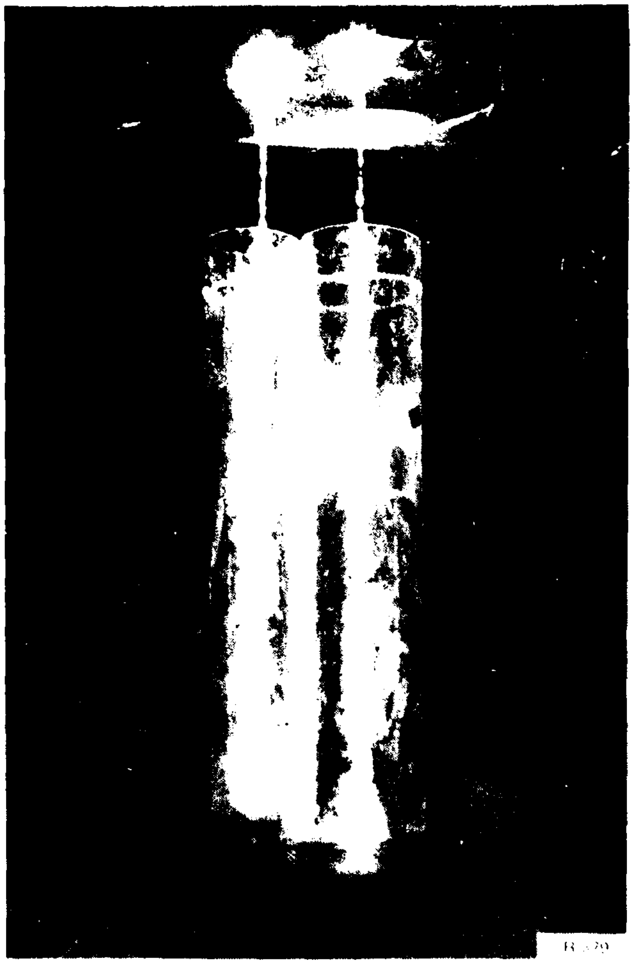


Fig. 4 — An open shutter photograph of the plasma beads produced by laser-induced, aerosol-initiated air breakdown. Note that when this photograph was taken, two plastic insulating tubes were being used, one around each plasma column

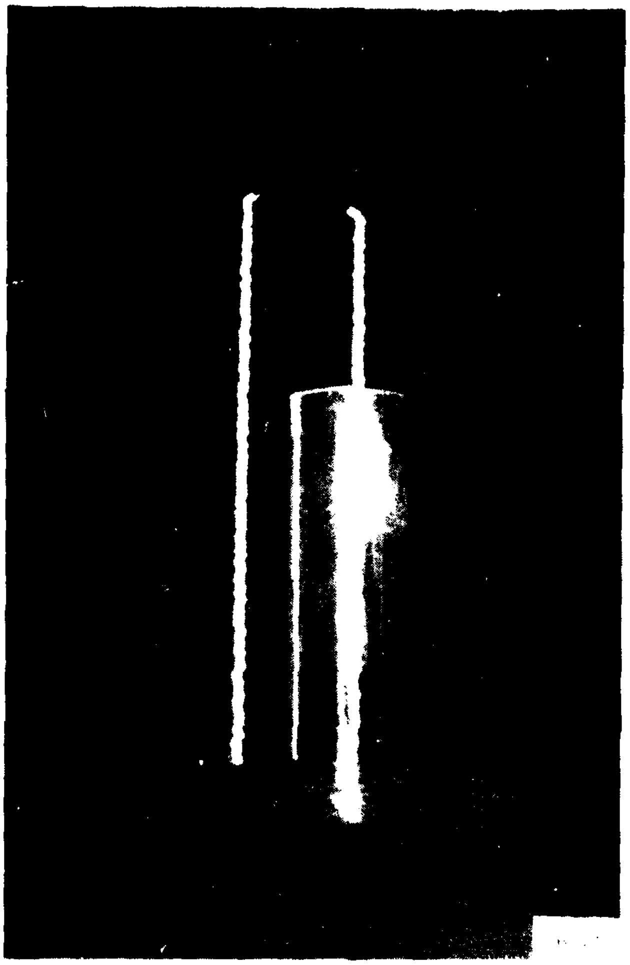


Fig 5 — An open shutter photograph of the plasma antenna produced by the discharge of the Marx generator. Each plasma column is 67 cm tall

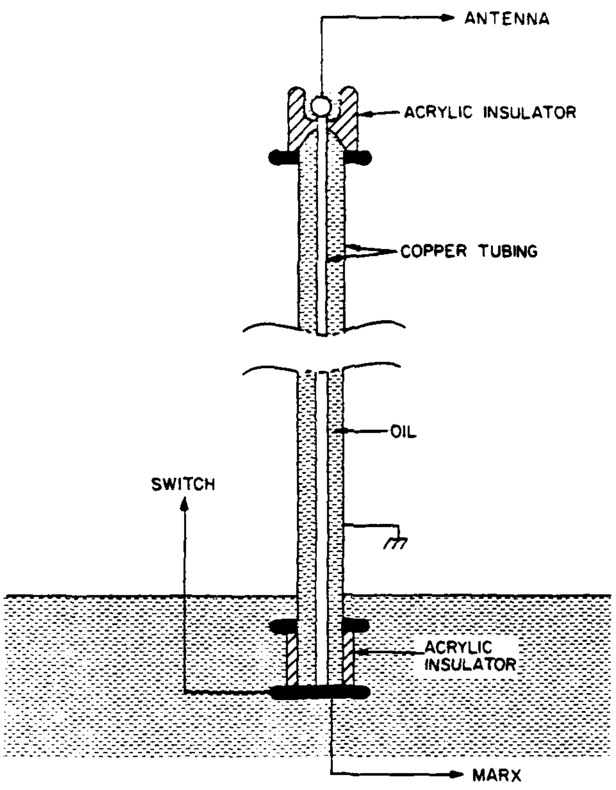


Fig. 6 — A schematic diagram of the coaxial high voltage line

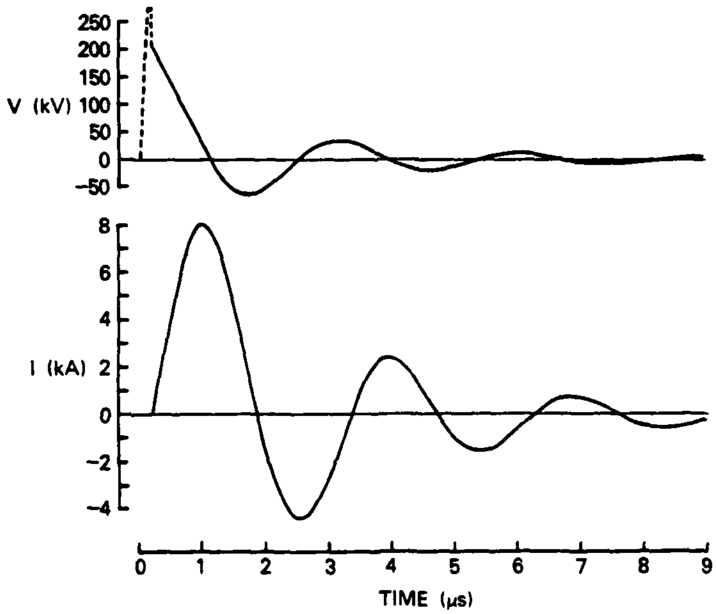


Fig. 7 — Typical characteristics of the discharge produced by the Marx generator. V is the output voltage of the generator and I is the discharge current.

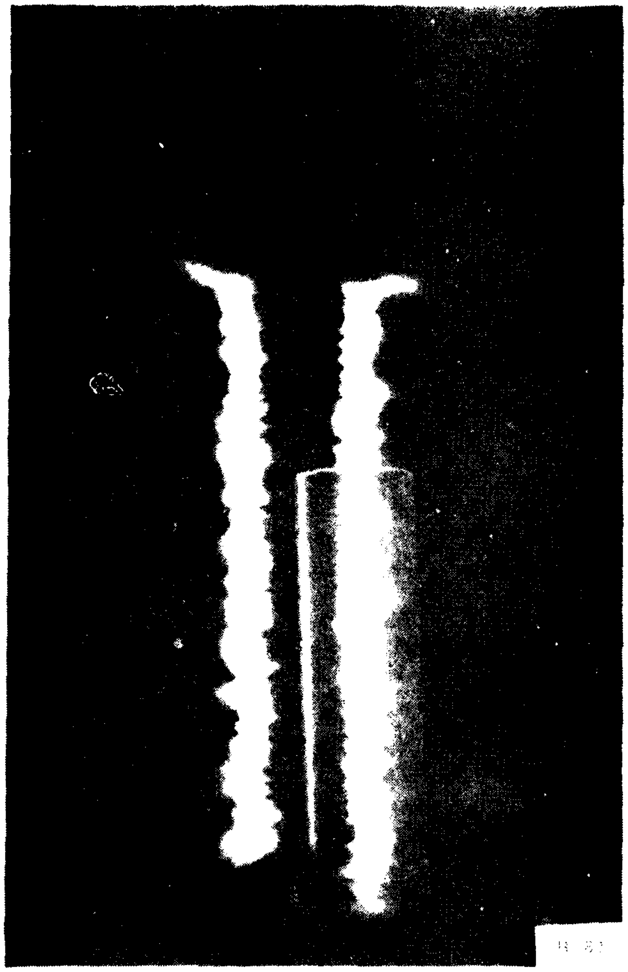


Fig. 8 — An open shutter photograph of the plasma antenna sustained with a secondary discharge.

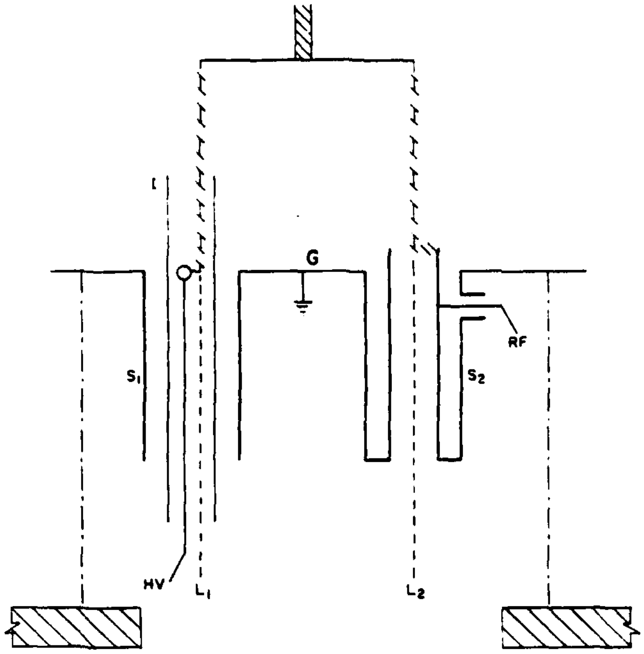


Fig. 9 — A schematic diagram of the plasma antenna showing how the high voltage, RF, and ground connections were made. L_1 and L_2 represent the paths of the two laser beams; HV labels the wire coming from the top of the high voltage coaxial line; S_1 and S_2 are the two tuned stubs; I is the lucite insulating tube; G is the ground plane; and RF indicates the point at which the RF signal is injected.

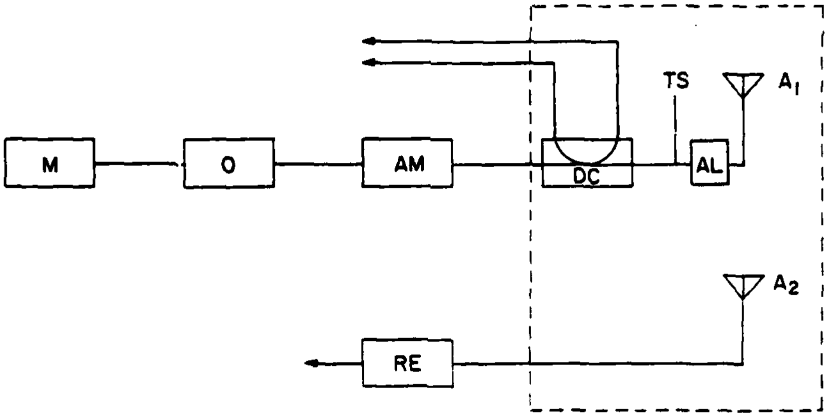
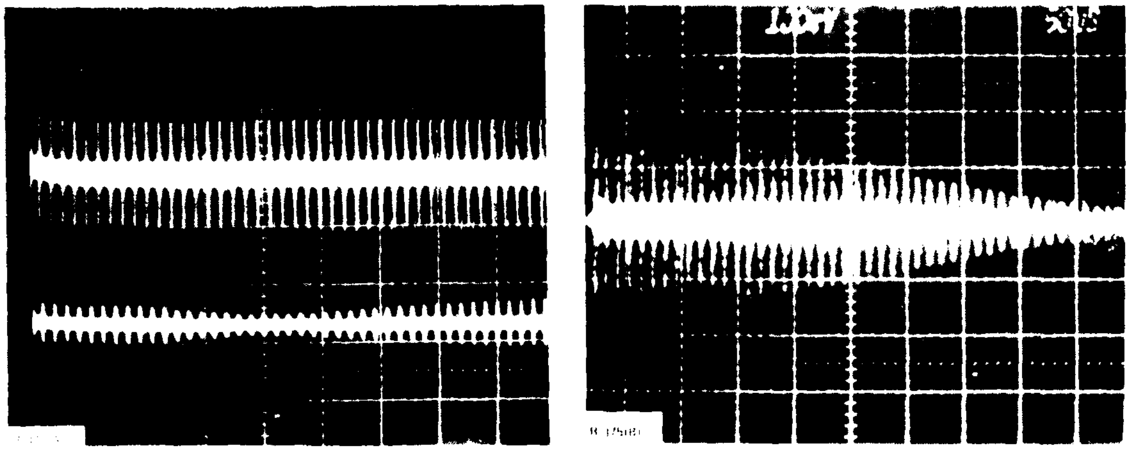


Fig. 10 — A diagram showing the RF system.

MOD	is a pulsed modulator,
OSC	is the RF oscillator,
AMP	is the RF amplifier,
DDC	is the dual directional coupler,
TS	represents a tuned stub,
AL	is a section of transmission line with adjustable length,
A_1	is the plasma antenna,
A_2	is the second antenna,
REC	is the receiver.

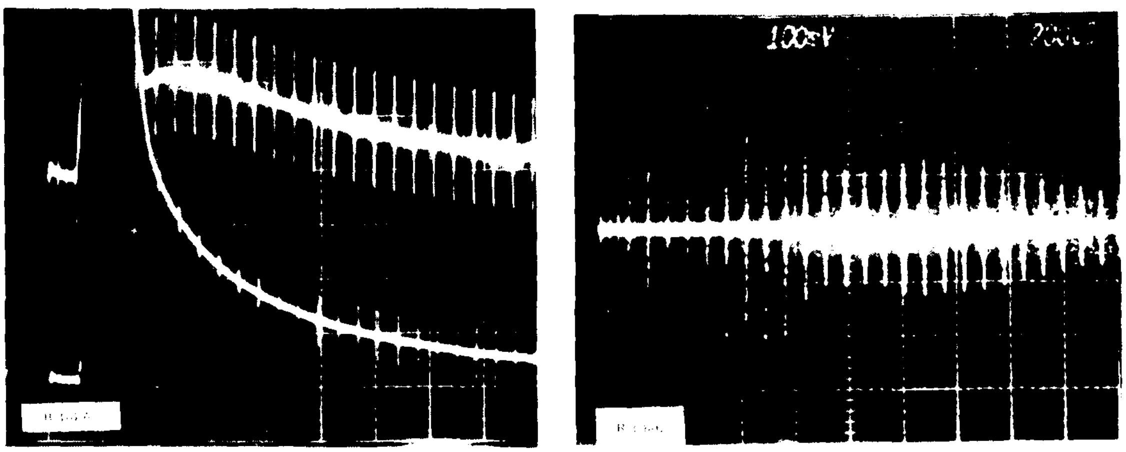
Only those items enclosed by the dashed line were located on the roof.



(a) upper — the signal from the amplifier.
lower — the signal reflected from the plasma antenna.

(b) the signal received on the second antenna.

Fig. 11 — Oscillograph records obtained using the plasma antenna produced by the laser/Marx discharge as the transmitting antenna. In each case one large horizontal division represents 50 μs



(a) upper — the signal from the amplifier.
lower — the signal reflected from the plasma antenna.

(b) the signal received on the second antenna

Fig. 12 — Oscillograph records obtained using the plasma antenna produced by the laser/Marx plus sustainer discharges as the transmitting antenna. In each case one large horizontal division represents 200 μs

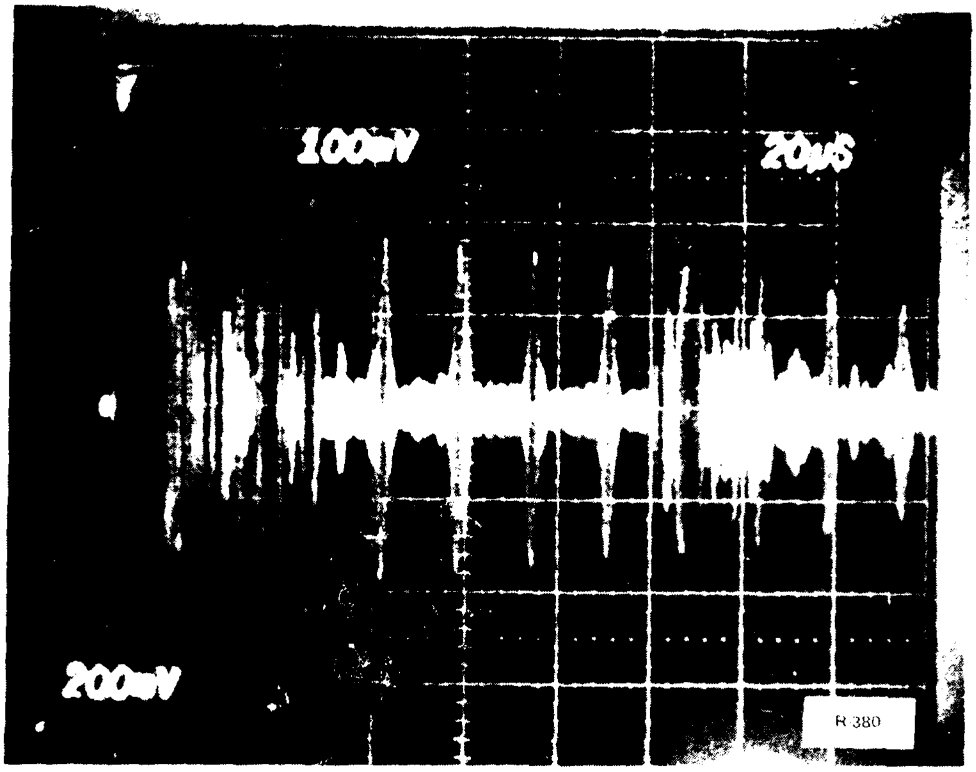


Fig. 13 — An oscillograph record obtained using the plasma antenna produced by the laser/Marx discharge as the receiving antenna.

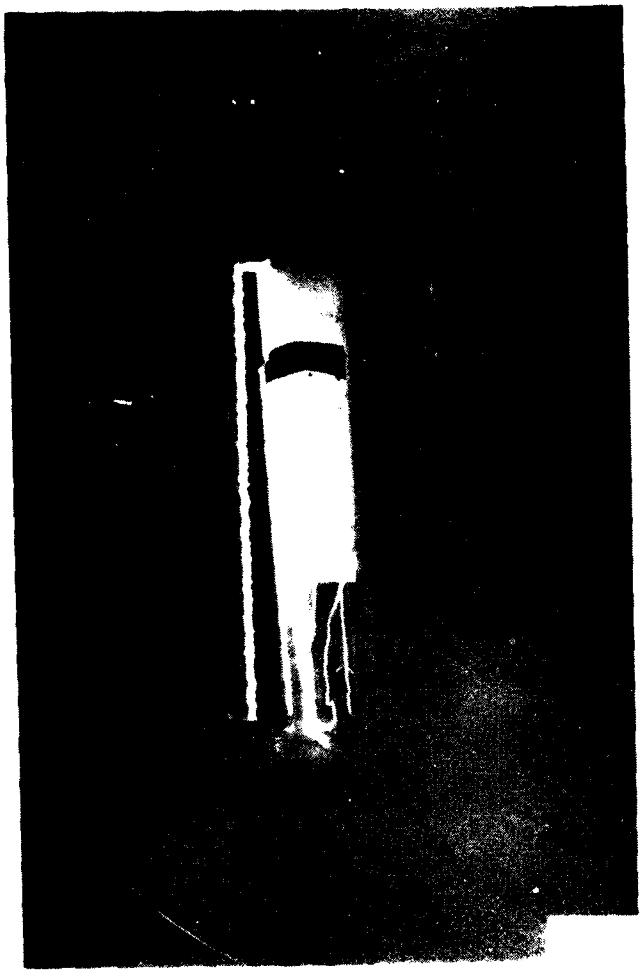


Fig. 14 — An open shutter photograph of the plasma antenna produced without using a metallic conductor to mark the top of the discharge path